A SYSTEMATIC METHOD FOR HYGROTHERMAL ANALYSIS OF BUILDING CONSTRUCTIONS USING COMPUTER MODELS

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ABSTRACT

Knowledge of the expected long-term performance of building envelopes subjected to simultaneous heat and moisture transport is critical during the design stage. The last few years a number of practical hygrothermal simulation models have been developed that can be used to analyse the combined heat and moisture behaviour of building constructions. However, hygrothermal analysis using computer-tools is not a straightforward task. In this paper is presented a general systematic method for hygrothermal analysis of building constructions by the use of simulation models. The method is applied on a design case of a wood frame wall, evaluating the risk for mould growth within the construction.

1. INTRODUCTION

Moisture damages has been identified as one of the main reasons for building envelope deterioration. When regarding only the building envelope it is estimated that about 75 - 90 % of all damages are caused by moisture (Trechsel, 1994). More recently recognized are the potential serious health hazards of mould and other organisms which flourish in buildings and constructions with excessive moisture.

Analysis of the hygrothermal behaviour of a building construction can be done through field and laboratory experiments and through modelling and calculations of the time dependent HAM-processes (HAM = "combined heat, air and moisture"). Until recently, it has not been common practice to make moisture transport calculations beyond the very simple steady state calculation of vapour diffusion, sometimes referred to as the Glaser method. However, today a lot of different simulation tools for hygrothermal analysis of building constructions exist internationally. An overview of 37 existing simulation tools is given by Hens (1996). The most advanced research tools are capable of simulating the simultaneous and coupled processes of vapour diffusion, capillary flow, vapour flow by air convection (forced and natural) and heat transfer by conduction, radiation, latent heat and enthalpy transfer in two dimensions. The commercially available HAM-models however are usually more simplified versions, typically one dimensional tools omitting air flow, e.g., MATCH (Pedersen, 1990) and 1D-HAM (Hagentoft, 1993).

HAM-tools have a variety of application areas for potential users such as building designers, consultants in building physics, producers of building materials and components and researchers. However, hygrothermal analysis using HAM-tools is not a straightforward task. The objective of this paper is to systematise a general method for how HAM-models best should be employed in hygrothermal analysis of building constructions. A lot of the input data to the models are uncertain and difficult to define properly, such as the outdoor and indoor climatic conditions, the material properties and the initial conditions. In addition the process of doing a hygrothermal analysis includes a lot of other choices and decisions that are critical for the accuracy and reliability of the analysis work. These choices and decisions touches aspects such as statistical approach, choice of simulation tool, cases to be simulated, analysis of simulated hygrothermal conditions, performance criteria and methods for evaluation of performance and risk for moisture damage. A systematic approach to deal with these aspects and problems will be a way to enhance the reliability of hygrothermal analysis by the use of simulation tools.

2. THE METHOD

The method proposed is closely based on experiences and information documented in (Geving, 1997). The method contains four main components*; 1) Problem definition, 2) Simulation set-up and input parameters, 3) HAM-simulations* and *4) Analysis of hygrothermal performance*. An overview of the various tasks included in the four components of the method is given in Table 1.

The method described is meant to be a general method, i.e., it might be used for very different purposes such as the design of a new construction at a specific location or evaluation of measurements by the use of HAM-tools. This imply that some of the tasks and subtasks defined for each component of the method may not be necessary to include in the analysis work. The method can be used as a checklist; i.e., the user must decide what components and tasks he wants to use or give extra attention. On the other hand; going through every task of this method will probably add extra accuracy and reliability to the hygrothermal analysis. The order of the various tasks included in the method will vary in practice, the order given in this paper is only meant as a guideline.

Table 1 Overview of the tasks included in the four components of the systematic method for hygrothermal analysis of building constructions using HAM-models.

COMPONENTS & TASKS
Level 1: Problem definition 1. Objectives 2. Construction 3. Moisture sources 4. Mechanisms for heat and moisture transfer 5. Possible performance problems 6. Time and costs to be used 7. Needed accuracy
Level 2: Simulation set-up and input parameters A. Simulation set-up 1. Types of performance checks 2. Statistical approach 3. Choice of simulation tool 4. Preliminary simulation 5. Cases to be simulated B. Input parameters 1. Outdoor climatic data 2. Indoor climatic data 3. Material properties 4. Initial conditions 5. Other input data
Level 3: HAM-simulation 1. Preparations/formatting of input parameters 2. Simulation 3. Control/preparation of output data
Level 4: Analysis of hygrothermal performance A. Analysis of hygrothermal conditions 1. Accuracy and reliability of simulation results 2. Reasons for the hygrothermal behaviour 3. Possible variation of the results B. Evaluation of performance 1. Find the performance value(s). 2. Evaluate the performance 3. New cases

Some of the tasks described in Table 1 are relatively straightforward, such as the tasks of "Level 3 - HAM-simulation". Other tasks are however more difficult, such as the choice of statistical approach, outdoor and indoor climatic data and material properties in "Level 2 - Simulation set-up and input parameters". Furthermore each of the tasks given in Table 1 can be divided in several subtasks. For a more thorough description of the method the interested reader is referred to (Geving, 1997).

3. APPLICATION : EVALUATION OF A WOOD FRAME WALL WITHOUT VAPOUR BARRIER

In this chapter the method presented in Chapter 2 is applied on a practical problem. The analysis work is presented according to the four levels of the method.

3.1 Problem definition

A vapour retarder typically has two functions in a building element. The first is to make the construction airtight so as to prevent moisture flow by water vapour convection, and the second is to reduce water vapour diffusion. In a cold climate such as in Norway it is accepted practice to use a vapour retarder at the inside of the building envelope. It has been argued that, if the air-tightness of the construction is handled otherwise, a vapour barrier is not needed at all. The purpose of this analysis is therefore to evaluate the durability performance of a wood frame wall without a vapour retarder. The wall is assumed to be airtight. The wind barrier used is relatively vapour tight (i.e., plywood), thereby representing relatively severe conditions regarding condensation at the wind barrier.

The building is located in Oslo, Norway. The design of the considered wall construction is presented in Figure 1. In this study the hygrothermal condition of the plywood layer is investigated. The important moisture related performance problems that may occur for this construction is mould growth on the wooden surfaces or rot. The fact that rot occur at higher humidity levels than mould growth, imply that if mould is not occurring rot will not occur either. In this analysis the risk for mould growth on the plywood surface is therefore investigated. The moisture sources considered are indoor and outdoor air humidity.

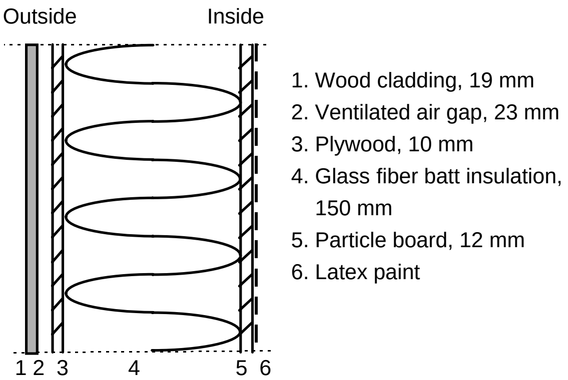


Figure 1 The constructional design of the wall

3.2 Simulation set-up and input parameters

Performance values and criteria

Using measurement results from (Viitanen, 1994), critical RH (RH_{cr}) for mould growth on pine and spruce material were assessed as functions of exposure time and temperature (T), see Table 2. Outside the temperature range [0°C, 50°C] it is assumed that no mould growth can occur.

Table 2 Critical RH (RH_{cr}) for mould growth on pine and spruce material as function of exposure time and temperature

	Temperature range		
	[0°C, 5°C〉	[5°C, 15°C〉	[15°C, 50°C〉
2 weeks	98 %	94 %	89 %
4 weeks	96 %	92 %	87 %
12 weeks	88 %	81 %	80 %

The performance values for RH ($RH_{p,i}$) and temperature ($T_{p,i}$) are calculated on a weekly basis for each exposure time (2, 4 and 12 weeks) from the following formula:

$$RH_{p,i} = \frac{\sum_{j=i-n+1}^{i} RH_{week,j}}{n} \qquad (1)$$

where $RH_{week,j}$ is the average simulated value for RH of the inside plywood surface for week j, i is the week for which $RH_{p,i}$ is calculated and n is the exposure time (n = 2, 4 or 12). The performance value for temperature for week i (used to determine RH_{cr}) is calculated in a similar way.

Statistical approach

A probabilistic approach closely based on the theory and methodology of structural reliability is applied. At a certain moment t the probability of failure can be determined by (Siemes, 1996):

$$P_{f,t} = P\{R(t) - S(t) < 0\} \qquad (2)$$

where $P_{f,t}$ is the probability of failure at time t and R(t) and S(t) are instantaneous physical values of the generalised resistance and the generalised load at the moment t. Eq. 2 apply for all t in the time interval (0,T) and T is the time of particular interest, e.g., the lifetime of the construction or one single year. All kinds of losses of the required performance, e.g., the loss of bearing capacity or visual unfitness, can be treated as failure. In this case the occurrence of mould growth is treated as failure. The design procedure is worked out in such a way that the failure probability is restricted:

$$P_{f,T} = P\{R(t) - S(t) < 0\}_T < P_{target} \qquad (3)$$

where $P_{f,T}$ is the probability of failure of the structure within T and P_{target} is the accepted maximum value of the probability of failure. This method is illustrated in Figure 2 for a simulation period of one year.

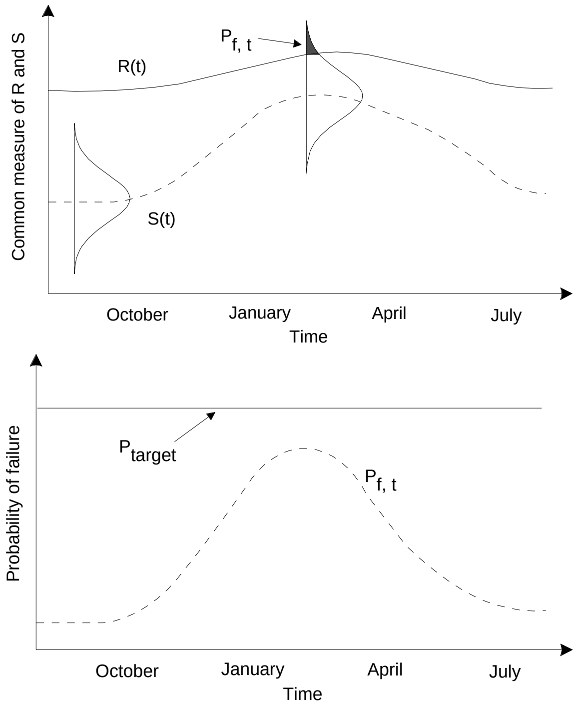


Figure 2 Illustration of probabilistic method for a simulation period of one year.

For this investigation the common measure of R and S is relative humidity. R is the critical relative humidity (RH_{cr}) according to Table 2, while S is the relative humidity of the inside plywood surface ($RH_{p,i}$) calculated according to Eq. 1. The simulation period T is one year. P_{target} was chosen to be 10%. Considering continous distribution of S the failure probability $P_{f,t}$ can be determined by:

$$P_{f,t} = 1 - \int_0^{RH_{cr}} f_{S,t}(RH)\,d(RH) \qquad (4)$$

where $f_{s,t}$ (RH) is the probability density function of the load S at time t.

To find the distribution of the load S the Monte-Carlo simulation method was applied. Applied on HAM-problems the method may include the following steps:

1. All uncertain input parameters are assigned a definite probability distribution.
2. One value is selected at random for each input based on its probability of occurrence.
3. A deterministic simulation using the selected input parameters from point 2 are performed and the output result (load S) are saved.
4. Point 2 - 3 are repeated N times.

5. The output results (load S) are analysed for statistical information.

For this investigation all uncertain input parameters and the load S were assumed to be normally distributed, and a number of 60 runs were used in this Monte-Carlo simulation

Computer model
The commercially available program 1D-HAM (Hagentoft, 1992) was employed to calculate the hygrothermal conditions of the wall. The model solves the coupled transient heat and mass transfer in one dimension, taking the hygroscopicity of the materials into account. The program considers moisture transfer by vapour diffusion and convection and uses simplified material properties, e.g., constant transport coefficients. For a more thorough description of the program see (Hagentoft, 1992).

Input data
For a design situation it is important that the climatic data represents a more severe moisture load than the average climate. Hourly weather data for 1991 from Oslo was selected for this design case, the selection of that particular year was made from the period 1975-1994 according to a method for finding representative weather data for moisture design calculations described in (Geving, 1997). The indoor air temperature was set like a constant value of 21 °C, while the air humidity difference between indoor and outdoor air Δv was assumed to be normally distributed (μ = 3.3 g/m^3 and σ = 1.0 g/m^3), based on measurements of indoor climate in single and multi family houses (Tolstoy, 1993).

Required material data for the simulations are the thermal conductivity λ (W/mK), the volumetric heat capacity C (J/m^{3}K), the moisture diffusion coefficient δ_v (m^2/s) and the sorption isotherm w(ϕ) (kg/m^3). Here w (kg/m^3) is the moisture content mass by volume, and ϕ (%) is the relative humidity. Simplified sorption isotherms are used. A sorption curve is given by two straight lines between the points (ϕ = 0, w = 0), ($\phi = \phi_1$, w = w_1) and (ϕ = 100, w = w_2). All uncertain material parameters are assumed to be normally distributed. Mean values and standard deviation for the material parameters used in the Monte-Carlo simulation are given in Table 3. The material data used as basis for the selection of mean values and standard deviation are mostly collected from the material database described in (Kumaran, 1996).

The wood cladding and ventilated air gap is modelled as one equivalent material layer, with a thermal and vapour resistance of respectively (μ = 0.06 m^{2}K/W, σ = 0.02 m^{2}K/W) and (μ = 260 s/m, σ = 0). The latex paint is included as an extra vapour resistance (Z_v) in the interior surface vapour resistance of (μ = 2.2·10^4 s/m, σ = 1.1·10^4 s/m).

Table 3 Data for materials used in the Monte-Carlo simulation, with mean values μ and standard deviation σ, ($\mu \pm \sigma$).

Parameters	Plywood(2)	Glass fiber	Particle board
λ (W/mK)	0.13 ± 0.02	0.039 ± 0.03	0.10 ± 0
C (MJ/m^{3}K)	1.1 ± 0.19	0.002 ± 0	1.3 ± 0
δ_v (10^{-6} m^2/s)	0.87 ± 0.54	19.5 ± 2.7	0.59 ± 0.23
ϕ_1 (%)	87.5 ± 5	95 ± 0	80 ± 0
w_1 (kg/m^3)	120 ± 10	0.41 ± 0.1	80.5 ± 0
w_2 (kg/m^3) (1)	210	0.9	210

(1) w_2 is given the same relative deviation from the mean as for w_1.
(2) δ_v is not allowed to be chosen below 3.63·10^{-8} m^2/s.

Initial moisture conditions are chosen to be approximately equal to a relative humidity of 70%. The solar absorption factor is assumed to be normal distributed (μ = 0.5, σ =0.15). The thermal surface resistance for the outdoor and indoor surface are 0.04 m^{2}K/W and 0.13 m^{2}K/W respectively. The exterior moisture surface resistance is 60 s/m, while the interior surface resistance includes the dominating resistance of the latex paint. The wall is oriented to the north and the simulation period is 52 weeks from 1. October to 30. September.

3.3 HAM-simulation

The tasks from this level of the method is not mentioned here, with an exception for the limitations and simplifications of the simulations; i) One-dimensional approximation to three-dimensional reality, i.e., studs and bottom/top-plates are not included and effect of internal convection is omitted, ii) Air leakages caused by non-idealities (workmanship effects) such as cracks, holes and air gaps are not included, iii) The ventilated air gap between exterior wood cladding and the plywood is modelled as a conductive layer, i.e. the vertical air flow is omitted, iv) Capillary moisture flow is not included, v) Effect of built in moisture is not considered, and vi) Constant material properties are used.

3.4 Analysis of hygrothermal performance

Results
The results of the Monte-Carlo simulation with 1D-HAM are presented in Figure 3. During the winter period it can bee seen that the RH of the plywood surface is between 70% and 100%, i.e., there is a high risk for mould growth. To investigate the reliability

of the results a similar construction was simulated with the one-dimensional HAM-model MATCH (Pedersen, 1990). As far as possible the same input parameters and climatic data were used, but instead of using the material parameters given in Table 3 the material data base of MATCH was used. The result of the MATCH-simulation is shown in Figure 5 together with the 1D-HAM results. As can bee seen the results from the MATCH model is quite similar to the mean results from 1D-HAM. This indicate that the accuracy and reliability of the results from 1D-HAM are relatively good, at least when considering the accuracy of the model.

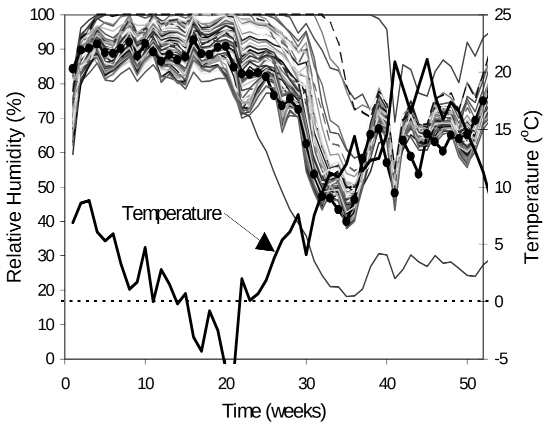


Figure 3 The results of the Monte-Carlo simulation (60 runs) with 1D-HAM. Weekly average RH and temperature of the inside plywood surface. For RH all 60 runs are shown, while temperature is given as the average of all runs.

To investigate whether the assumption that the results (i.e., the weekly average RH at inside plywood surface) are normally distributed are correct, the frequency distribution of RH is plotted for three moments in Figure 4. The assumption of normal distribution seem to apply relatively good for this case, although some deviation can be observed.

Evaluation of performance

In Figure 5 the minimum critical RH (RH_{cr}) as a function of temperature and exposure time is plotted together with the calculated results of 1D-HAM and MATCH. As can be seen the critical RH is well below the mean calculated RH for a period between week 10 and 20, thereby indicating a risk for mould growth above 50%. The calculated probability for mould growth is presented in Figure 6 as function of time and exposure time. Figure 6a shows that the exposure time of 12 weeks is critical, giving a probability for mould growth of approximately 70 % prevailing for a period of 2 months.

To investigate the sensitivity of the various input parameters on the moisture conditions of the plywood layer the Spearman rank-correlation coefficient, e.g. see (Press et al., 1986), was calculated between the input parameters and the average RH of the surface of the plywood for the period week #5-16. The calculated rank coefficients are given in Table 4. The input parameter influencing the most on the results is the vapour permeability of the plywood.

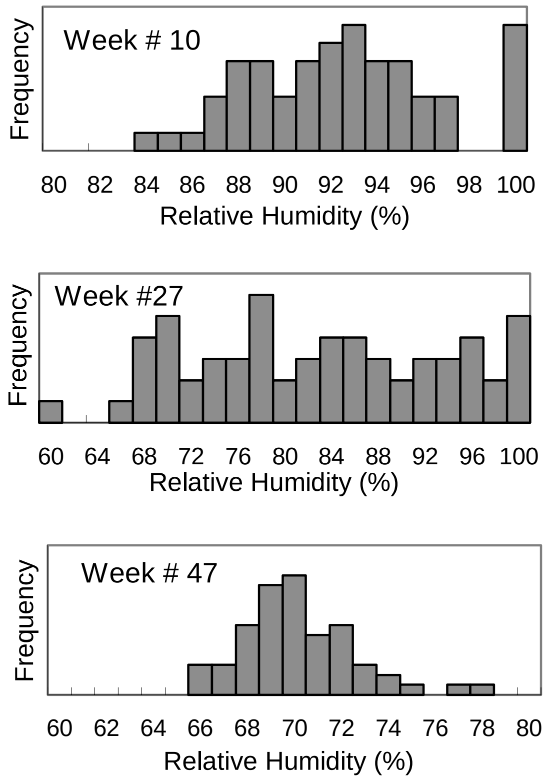


Figure 4 Frequency distributions of RH at inside plywood surface for the Monte-Carlo simulation (60 runs) at three different moments during the simulations.

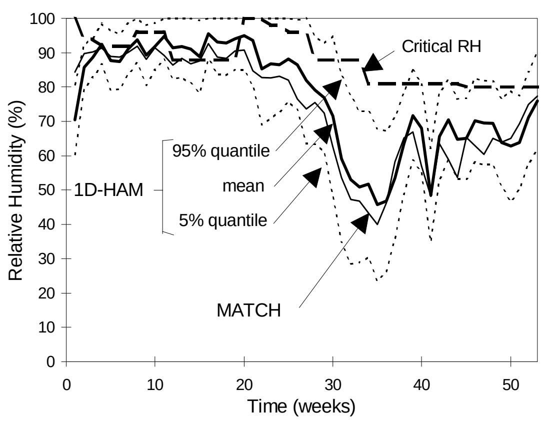
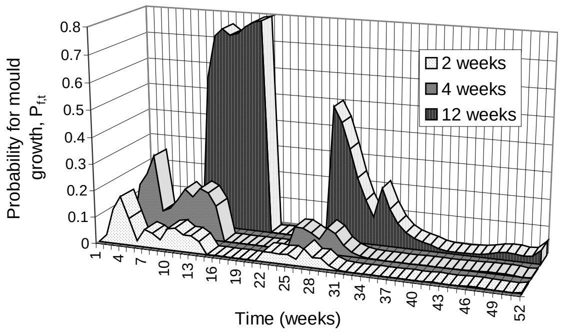
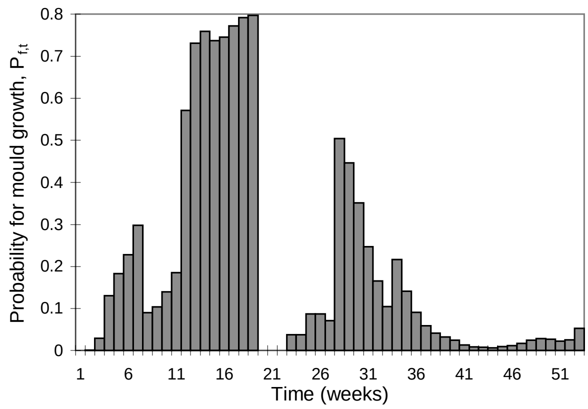


Figure 5 1D-HAM results (mean, 5 and 95 % quantile) and MATCH result plotted together with the minimum critical RH (RH_{cr}) dependent of temperature and exposure time. Weekly average RH of the inside plywood surface.



a. Probability for mould growth dependent of exposure time



b. Maximum probability for mould growth

Figure 6 Probability for mould growth on the inside plywood surface.

Table 4 The Spearman rank-correlation coefficient r_s between input parameters and the average RH of the inside surface of the plywood for the period week #5-16

Parameter	r_s
Vapour permeability (δ_v) plywood	-0.85
Moisture supply (Δv)	0.36
Sorption curve coeff. (ϕ_1) plywood	0.31
Thermal conductivity (λ) plywood	0.28
Thermal conductivity (λ) glass fiber	-0.19
Sorption curve coeff. (w_1) plywood	0.18
Vapour resistance (Z_v) paint	-0.16
Vapour permeability (δ_v) particle board	0.13
Solar absorption factor (α)	0.11
Heat capacity (C) plywood	0.10
Vapour permeability (δ_v) glass fiber	0.06
Sorption curve coeff. (w_1) glass fiber	-0.04
Thermal conductivity (λ) ventilated cladding	-0.01

Conclusions

The probability for mould growth is found to be approximately 70% for a period of eight weeks for a relatively severe outdoor climate. Since the accepted maximum value for probability for mould growth was chosen to be 10%, the considered wood frame wall construction can not be accepted. This indicate that a vapour barrier is needed for this type of construction, alternatively a more vapour open wind barrier might yield better moisture conditions.

4. OVERALL CONCLUSIONS

A systematic general method for hygrothermal analysis of building constructions by the use of simulation models is presented. The method can be used as a checklist, i.e., the user must himself decide what components and tasks he wants to use or give extra attention. The objective of the method is to enhance the reliability of hygrothermal analysis by the use of simulation tools. The method contains four components*; 1) Problem definition, 2) Simulation set-up and input parameters, 3) HAM-simulations* and *4) Analysis of hygrothermal performance*.

The method was applied on a design case of a wood frame wall employing a probabilistic approach and the risk for mould growth within the construction was evaluated.

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